JHEP, 06:106, 2017
Phys. Lett., B770:380– 402, 2017

Measurement of W/Z γ scatterings at LHC with Run-1 data and constraints on anomalous couplings

The Third China LHC Physics Workshop

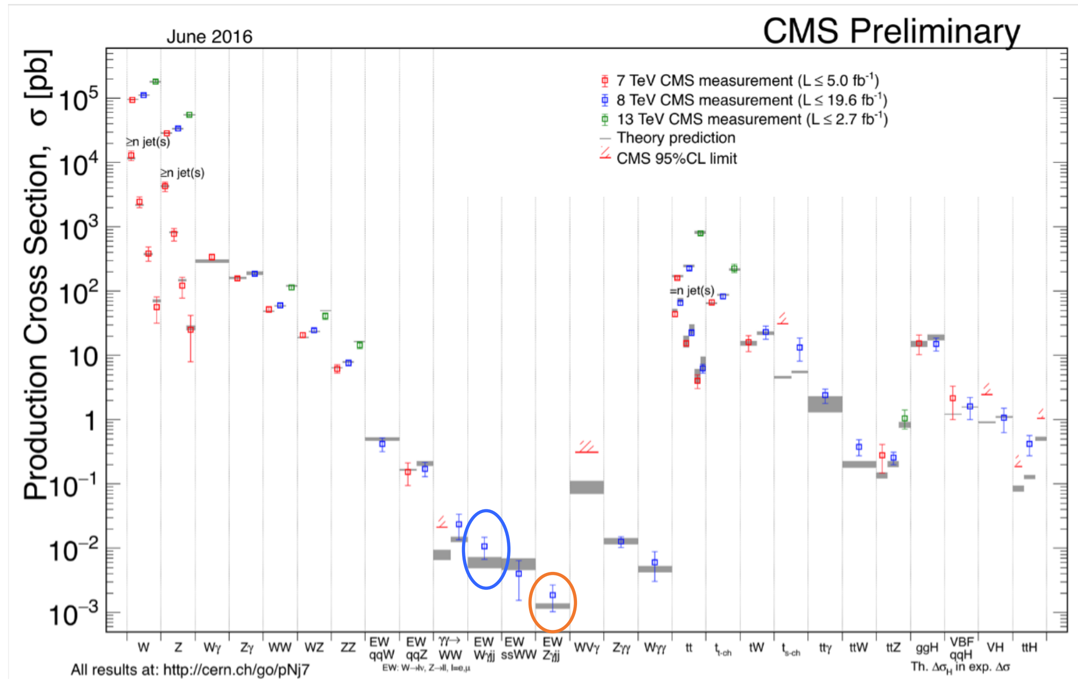
Daneng Yang for the CMS Collaboration

Dec 22nd-24th, 2017
Nanjing University, Nanjing

Motivations

Standard Model Physics group in the CMS experiment

- Novel and Precise Electroweak test
- Improve controls of backgrounds for new physics searches
- Improve measurements of gauge-boson self-interactions -- tri-linear interactions and quartic interactions



JHEP, 06:106, 2017

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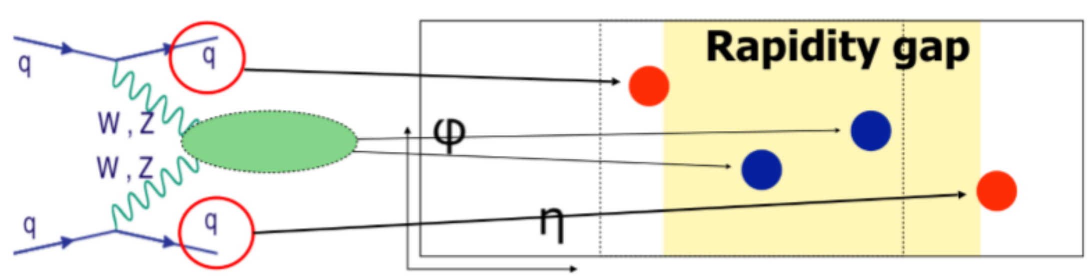
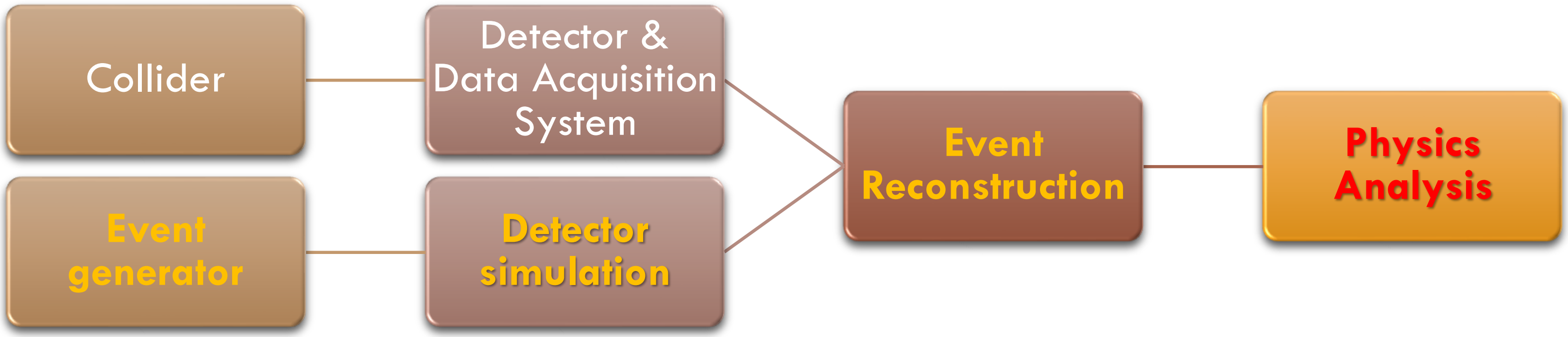
Pure EW production is sensitive to the gauge structure of underlying theory and can be sensitive to new physics

- ➢ **Large QCD-induced background**
- ➢ **Use vector boson fusion/scattering to enhance EW contribution**



The Analysis Framework

Analysis Framework



- Dataset
- **Event generation and simulation**
- Event reconstruction
- Physics analysis
    - Background modelling
    - Systematic uncertainties
    - Event selection and statistical analysis

Theoretical predictions rely on MC event generators:
MadGraph, Powheg, VBFNLO, Pythia, Sherpa …

Processes	Type
Signal: EWK $W\gamma$+2jets	MC
QCD $W\gamma$+*(0-3)jets* (MLM matching)	MC shape + data-driven normalization
$W\gamma$+jets/multi-jets with one jet fakes a photon	Data + MC truth
γ+jets with one jet fakes an electron	Data
$t\bar{t}\gamma$	MC
Single top	MC NLO
$WZ\gamma$	MC
WW	MC NLO
ZZ	MC NLO
QCD $Z\gamma$+(0-3)jets (MLM matching)	MC

Analysis Framework

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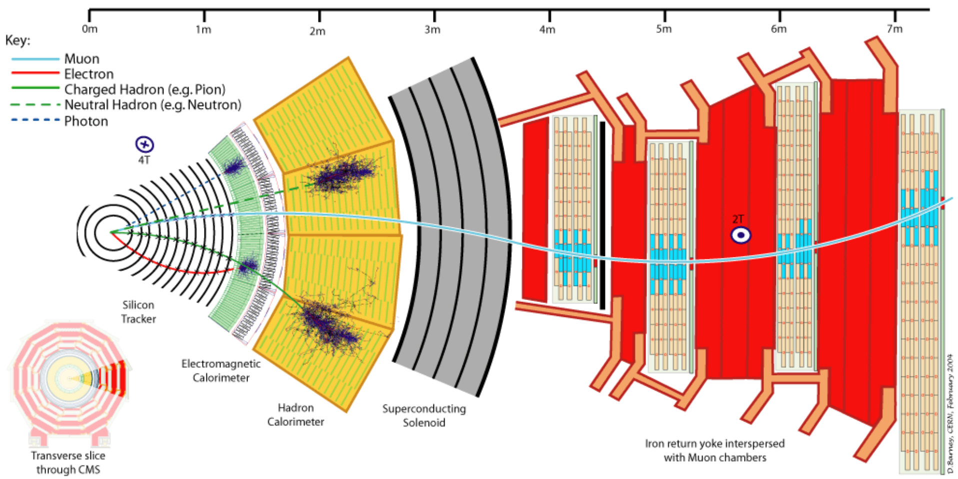

The Particle Flow algorithm

- ➢ Attempt to reconstruct all stable particles in an event
- ➢ Combine Information from sub-detectors in best possible way
- ➢ List of particles is returned

Higher level physics objects can be built from list of particles

1. Missing transverse energy
2. Jets
3. b-tagged jets
4. Hadronic taus*

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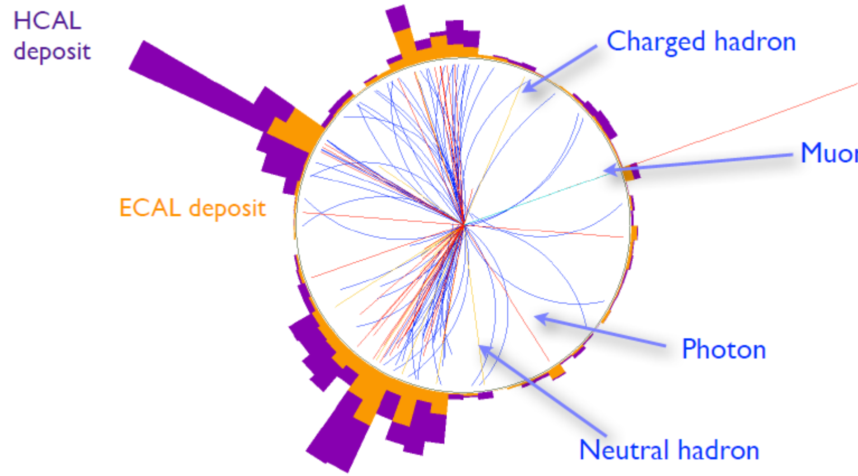

Figure from Florian Beaudette's (LLR) talk

Muon

- ID efficiency 80%, veto ID efficiency 90%
- PF based relative isolation with DeltaBeta correction, RelIsoPF < 0.12

Electron

- Cut based medium ID; ID eff. 80%, veto ID eff. 90%
- PF based relative isolation with EA correction

Jets

- Anti-k_T PF jets with $\Delta R = 0.5$
- Charged Hadron not from PV removed
- Jet Energy Correction

Missing Transverse Energy (Wgamma)

- PF MET > 35 GeV
- Type 1 corrected (energy scale)
- $\Delta\phi_{MET.j1} > 0.4$, $\Delta\phi_{MET.j2} > 0.4$

Photons

- 2012 cut base ID
- PF isolation with EA correction
- $E_T > 22$ GeV
- Barrel region only ($|\eta| < 1.4442$)
- $\Delta R_{j\gamma} > 0.5$, $\Delta R_{l\gamma} > 0.5$

Analysis Framework

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Data driven bakcgrounds:

Ordered with decreasing size

Electron mis-identified events can be suppressed using $|M_{\gamma e}$ - MZ$|$ > 10 GeV

Electron channel only

For VBS Wgamma

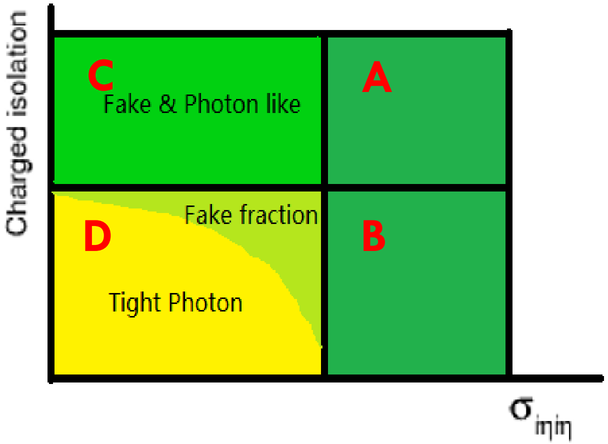
QCD
W/Z
γ+jets

Jet
fakes
photon

Jet
fakes
electron

Analysis Framework

Photon contamination



$$\frac{A}{B} = \frac{C}{D(QCD\ only)}$$

Fake photon fraction

$$(FF) = \frac{D(QCD\ only)}{D}$$

The normalized photon like jet sample provides photon contamination background for any kinematic distributions.

QCD Wγ+jets Mjj control region

(QCD Zγ+jets in VBS Zgamma)

Normalize the contribution at low mjj

- 200 GeV < Mjj < 400 GeV
- Base line selections

Muon channel

normalization scale factor: 0.772 ± 0.048

Electron channel

normalization scale factor: 0.773 ± 0.055

Theory K-factor from VBFNLO: 0.93 ± 0.27

γ+jets to electron contamination

The shape of MET is used to extract the electron **contamination rate**.

Method similar to the estimation of photon contamination.

Analysis Framework

- Dataset
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- **Physics analysis**
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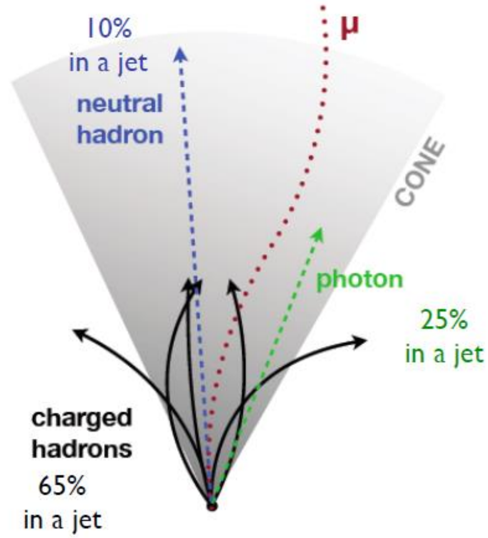


Small systematic uncertainties with data

- Luminosity 2.6% for rereco, 4.4% for prompt reco
- PU Modeling 1%
- Photon energy scale 1%
- Trigger 1%
- Lepton RECO/ID efficiency Scale factor 2%
- Jet energy scale and resolution uncertainty
- Jet anti-b tag uncertainty (Top background only)

Charged-hadrons and photons (90%) are measured better than neutral hadrons (10%)

- Tracking: resolution < 1%
- Photons: $2.7\%/\sqrt{E} \oplus 0.5\%$ barrel
- $5.7\%/\sqrt{E} \oplus 0.5\%$ endcaps
- HCAL resolution for hadrons: $120\%/\sqrt{E}$

From Florian Beaudette's (LLR) talk

Analysis Framework

- Dataset
- Event generation and simulation
- Event reconstruction
- **Physics analysis**
  - Background modelling
  - **Systematic uncertainties**
  - Event selection and statistical analysis

VBS Wgamma for example

- **Theoretical uncertainty: PDF unc. and Scale unc.** 10-25%, Scale unc. > PDF unc.
- **Uncertainties with background modelling**

□ Photon contamination background uncertainty:

- Sideband+stat.+Shape
- From 13% at $\mathrm{p_T^\gamma}$~25 GeV to 54% at $p_T^\gamma > 135\ \mathrm{GeV}$

□ Electron contamination background uncertainty:

- Statistical uncertainty:16.7%
- Systematical uncertainty: 5.2%

□ QCD Wγ+jets:

Normalization uncertainty. 6.2%(muon) / 7.1%(electron)

Additional uncertainty on the extrapolation from low Mjj to high Mjj

Analysis Framework

- Dataset
- Event generation and simulation
- Event reconstruction
- **Physics analysis**
  - Background modelling
  - **Systematic uncertainties**
  - Event selection and statistical analysis (Next section)

VBS Wgamma cont'd

- **Jet anti-b tag uncertainty**

  Scale factor 96.6% for combined secondary vetex algorism, with 2% uncertainty.

  This uncertainty is propagated to the signal region and leads to 8.3% uncertainty for the $t\bar{t}\gamma$ process and 22.6% uncertainty for the single top process.

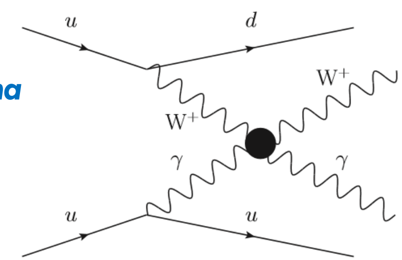
Source	Uncertainty
QCD $Z\gamma$ + jets normalization	22% ($400 < M_{jj} < 800$ GeV) 24% ($M_{jj} > 800$ GeV)
Fake photon from jet (p_T^γ dependent)	15% (20–30 GeV) 22% (30–50 GeV) 49% (>50 GeV)
Trigger efficiency	1.2% ($Z \to \mu^+\mu^-$), 1.7% ($Z \to e^+e^-$)
Lepton selection efficiency	1.9% ($Z \to \mu^+\mu^-$), 1.0% ($Z \to e^+e^-$)
Jet energy scale and resolution	14% ($M_{jj} > 400$ GeV)
$t\bar{t}\gamma$ cross section	20% [3]
Pileup modeling	1.0%
Renormalization/ factorization scale (signal)	9.0% ($400 < M_{jj} < 800$ GeV), 12% ($M_{jj} > 800$ GeV) (SM) 14% (aQGC)
PDF (signal)	4.2% ($400 < M_{jj} < 800$ GeV), 2.4% ($M_{jj} > 800$ GeV) (SM) 4.3% (aQGC)
Interference (signal)	18% ($400 < M_{jj} < 800$ GeV), 11% ($M_{jj} > 800$ GeV) (SM)
Luminosity	2.6%

Table of Uncertainties for the VBS Zgamma analysis

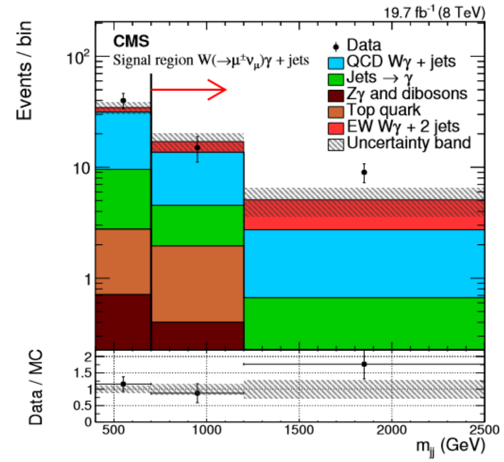
Cross section measurements

Data and MC Comparison

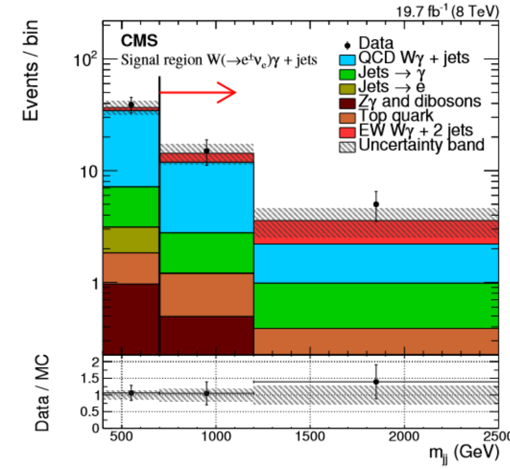
VBS Wgamma



Muon channels



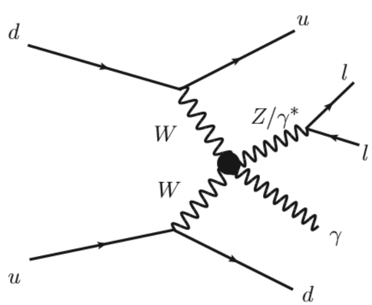
Electron channels

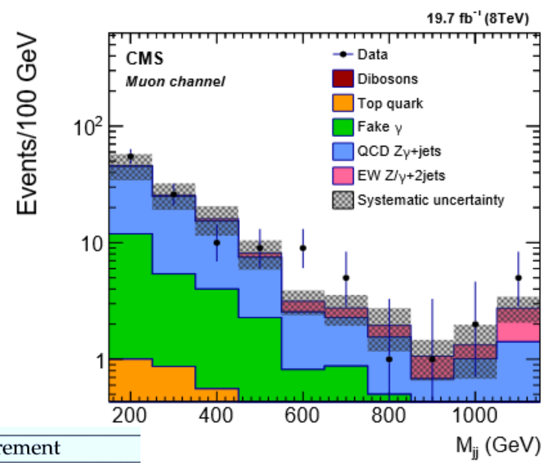


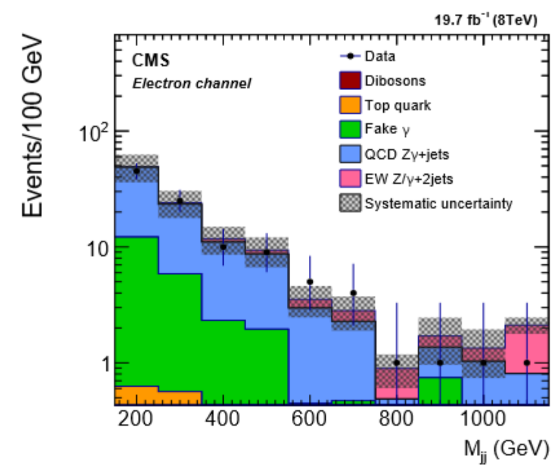
Arrow indicates signal region

- $|y_{W\gamma} - (y_{j1} + y_{j2})/2.0| < 0.6,$
- $|\Delta\phi_{W\gamma,dijet}| > 2.6,$
- $M_{jj} > 700$ GeV,
- $|\Delta\eta(j1, j2)| > 2.4.$

VBS Zgamma





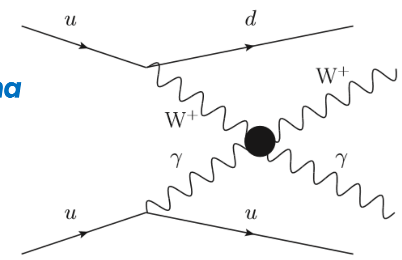


$$p_T^{j1,j2} > 30\,\text{GeV},\ |\eta^{j1,j2}| < 4.7$$
$$p_T^{\ell1,\ell2} > 20\,\text{GeV},\ |\eta^{\ell1,\ell2}| < 2.4$$
$$|\eta^{\gamma}| < 1.4442$$
$$M_{jj} > 150\,\text{GeV}$$
$$70 < M_{\ell\ell} < 110\,\text{GeV}$$

EW signal measurement
$p_T^{\gamma} > 25\,\text{GeV}$
$\lvert\Delta\eta_{jj}\rvert > 1.6$
$\Delta R_{j\ell} > 0.3,\ \Delta R_{jj,\gamma j,\gamma\ell} > 0.5$
$\lvert y_{Z\gamma} - (y_{j1} + y_{j2})/2\rvert < 1.2$
$\Delta\phi_{Z\gamma,jj} > 2.0$ radians
$M_{jj} > 400\,\text{GeV}$ with two divided regions
$400 < M_{jj} < 800\,\text{GeV}$ and $M_{jj} > 800\,\text{GeV}$

Wγ+2jets cross section measurement

VBS Wgamma



Observed limit	4.30
Expected limit (-2σ)	1.30
Expected limit (-1σ)	1.49
Expected limit (median)	2.01
Expected limit (+1σ)	3.47
Expected limit (+2σ)	6.09

Cross section measurement (EWK and EWK+QCD)

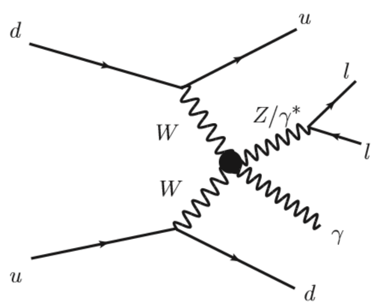
- **Fiducial region cross section**
  - $p_T^{j1} > 30$ GeV, $|\eta^{j1}| < 4.7$,
  - $p_T^{j2} > 30$ GeV, $|\eta^{j2}| < 4.7$,
  - $M_{jj} > 700$ GeV, $|\Delta\eta(j,j)| > 2.4$,
  - $p_T^l > 20$ GeV, $|\eta^l| < 2.4$,
  - $p_T^\gamma > 20$ GeV, $|\eta^\gamma| < 1.4442$,
  - $\not{E}_T > 20$ GeV,
  - $\Delta R_{j,j}, \Delta R_{l,j}, \Delta R_{\gamma,j}, \Delta R_{l,\gamma} > 0.4$.

Items	EWK measurement	EWK+QCD measurement
$\hat{\mu}$	$1.78^{+0.99}_{-0.76}$	$0.99^{+0.21}_{-0.19}$
EWK fraction (search region)	100%	27.1%
EWK fraction (fiducial region)	100%	25.8%
Observed (Expected) significance	2.67(1.52) σ	7.69(7.49) σ
Theory cross section (fb)	6.1 ± 1.2 (scale) ± 0.2 (PDF)	23.5 ± 6.6 (scale) ± 0.8 (PDF)
Measured cross section (fb)	10.8 ± 4.1 (stat.) ± 3.4 (syst.) ± 0.3 (lumi.)	23.2 ± 4.3 (stat.) ± 1.7 (syst.) ± 0.6 (lumi.)

Good agreement with theory predictions.

Zγ+2jets cross section measurement

VBS Zgamma



Expected significance: 2.1 σ
Observed significance: 3.0 σ

Cross section measurement (EWK and EWK+QCD)

- **Fiducial region cross section**

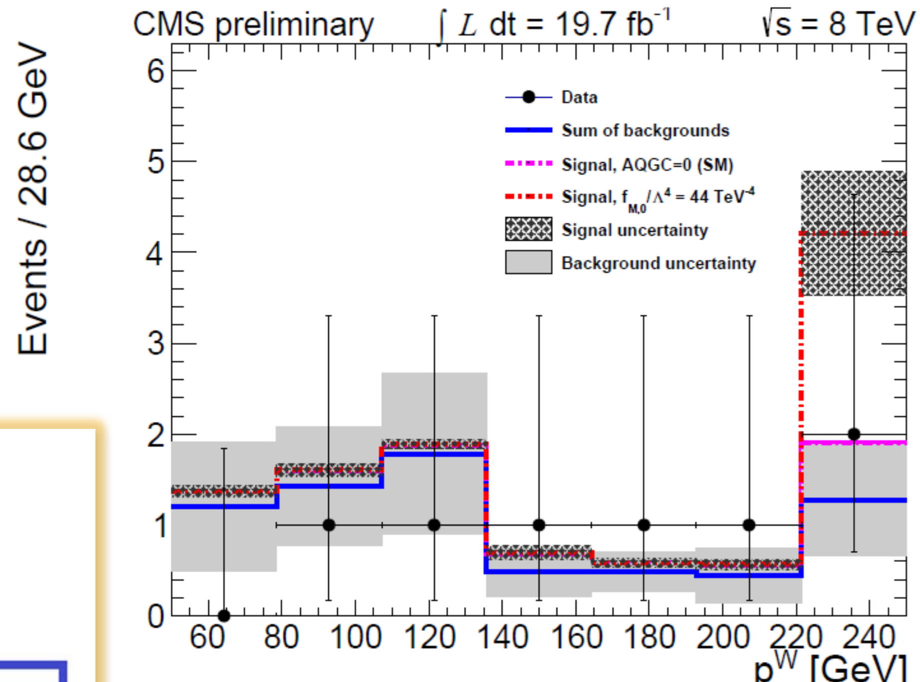
$$p_T^{j1,j2} > 30\,\mathrm{GeV},\ |\eta^{j1,j2}| < 4.7$$
$$p_T^{\ell 1,\ell 2} > 20\,\mathrm{GeV},\ |\eta^{\ell 1,\ell 2}| < 2.4$$
$$|\eta^{\gamma}| < 1.4442$$
$$M_{jj} > 150\,\mathrm{GeV}$$
$$70 < M_{\ell\ell} < 110\,\mathrm{GeV}$$
$$p_T^{\gamma} > 20\,\mathrm{GeV}$$
$$|\Delta\eta_{jj}| > 2.5$$
$$\Delta R_{jj,\gamma j,\gamma\ell,j\ell} > 0.4$$
$$M_{jj} > 400\,\mathrm{GeV}$$

Items	EWK measurement	EWK+QCD measurement
Observed (Expected) significance	3.0 (2.1) σ	5.7 (5.5) σ
Theory cross section (fb)	$1.27 \pm 0.11\,(scale) \pm 0.05(PDF)$	$5.05 \pm 1.22\,(scale) \pm 0.31(PDF)$
Measured cross section (fb)	$1.86^{+0.90}_{-0.75}(stat)^{+0.34}_{-0.26}(syst) \pm 0.05(lumi)$	$5.94^{+1.53}_{-1.35}(stat)^{+0.43}_{-0.37}(syst) \pm 0.13(lumi)$

Constraints on anomalous gauge couplings

Constraints on anomalous gauge couplings

We consider an effective field theory with SU(2)⊗U(1) gauge symmetry linearly realized and with higher dimensional operators containing pure quartic couplings.
Reference: arXiv:hep-ph/0606118



Comparison of predicted and observed distributions with electron and muon combined channels. The last p_T^W bin has been extended to include overflow contribution.

Likelihood based statistical study

$$t_{\alpha_{test}} = -2ln\frac{\mathcal{L}(\alpha_{test}, \hat{\hat{\theta}})}{\mathcal{L}(\hat{\alpha}, \hat{\theta})},$$

$$\mathcal{L}(A,\theta) = norm(\theta)\ \boxed{Poisson(N|\ S+B)}\ \boxed{\prod_n^N P(p^n_{T,W}, A)}$$

Modified selections for the aQGC study: VBS Wgamma

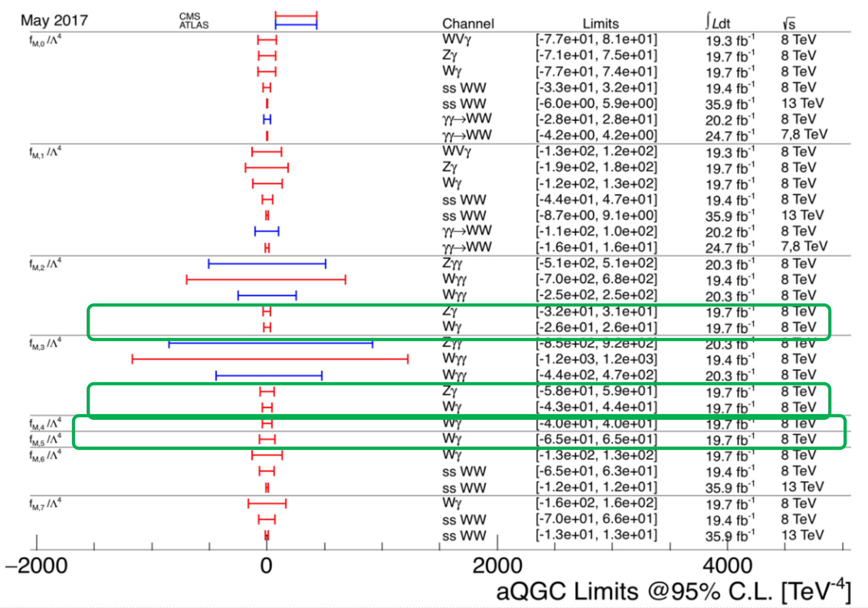
- p_T^γ > 200 GeV
- $|y_{W\gamma} - \frac{y_{j1}+y_{j2}}{2}|$ <1.2, $|\Delta\eta_{jj}|$>2.4

VBS Zgamma

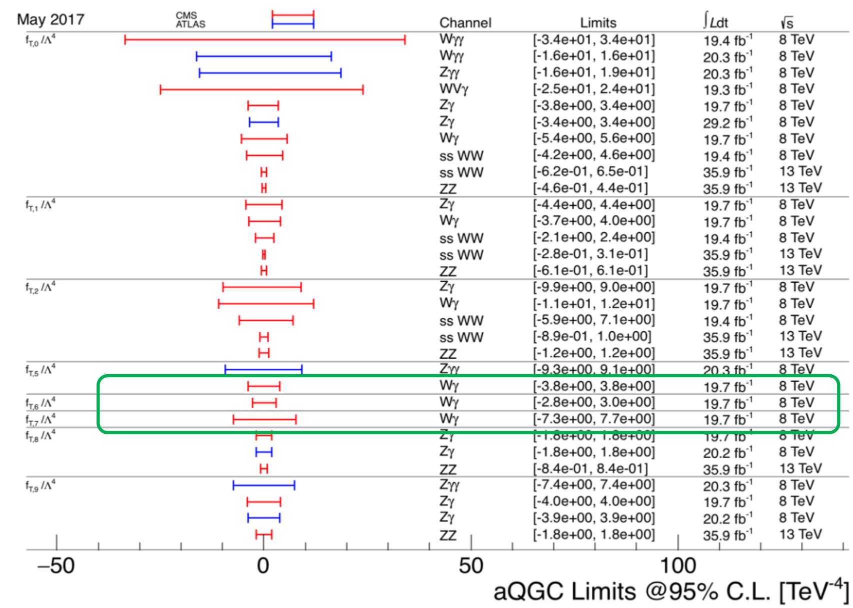
$p_T^{j1,j2} > 30$ GeV, $|\eta^{j1,j2}| < 4.7$
$M_{jj} > 400$ GeV, $\Delta\eta_{jj}$ >2.5
$p_T^{l1,l2} > 20$ GeV, $|\eta^{l1,l2}| < 2.4$
70 GeV $< M_{ll} <$ 110 GeV
$p_T^\gamma > 60$ GeV, $|\eta^\gamma| < 1.4442$

Comparison with existing limits

$L_{M,i}$: Operators containing $D_\mu\Phi$ and field strength



$L_{T,i}$: Operators containing just the field strength tensor



CMS EWK ss WW $\rightarrow \ell^{+/-}\ell^{+/-}$qq: using 19.4 fb^{-1} of 8 TeV pp collisions Phys. Rev. Lett. 114, 051801 (2015)

CMS $VW\gamma \rightarrow jj\ell\bar{\nu}\gamma$ triboson production with 19.3 fb^{-1} of 8 TeV pp collisions Phys. Rev. D 90, 032008 (2014)

CMS $\gamma\gamma \rightarrow W^+W^- \rightarrow e^+\mu^-$ scattering with 5.0 fb^{-1} of 7 TeV and 19.7 fb^{-1} of 8 TeV pp collisions Submitted to JHEP

CMS EWK qq $\rightarrow Z\gamma qq \rightarrow \ell^+\ell^-\gamma$qq: using 19.7 fb^{-1} of 8 TeV pp collisions CMS-PAS-SMP-14-018

CMS EWK qq $\rightarrow W\gamma qq \rightarrow \ell^+\nu\gamma$qq: using 19.7 fb^{-1} of 8 TeV pp collisions CMS-PAS-SMP-14-011

CMS $W\gamma\gamma \rightarrow \ell\bar{\nu}\gamma\gamma$ and $Z\gamma\gamma \rightarrow \ell^+\ell^-\gamma\gamma$ triboson production with 19.4 fb^{-1} of 8 TeV pp collisions Submitted to JHEP

ATLAS $W\gamma\gamma \rightarrow \ell\bar{\nu}\gamma\gamma$ triboson production with 19.3 fb^{-1} of 8 TeV pp collisions Phys.Rev.Lett. 115 (2015) 3, 031802

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

- Several results from 13 TeV analyses
- We still have most stringent limits for some of the parameters

Summary

- At 8 TeV LHC, we measured the VBS W/Z gamma scatterings in the CMS experiment. The significances wrt no EWK signal are found to be 2.7 (3.0) σ for W(Z) gamma scatterings.

- Cross sections of W(Z)gamma production in association with two jets are measured in the fiducial regions. Good agreements with the standard model predictions are observed.

- Experimental limits on dimension eight anomalous quartic gauge couplings $f_{M,0-7}/\Lambda^4$, $f_{T,0-2}/\Lambda^4$, and $f_{T,5-9}/\Lambda^4$ are set at 95% confidence level.

- *See Meng Lu's talk for an update of 13 TeV measurement.*